A Comparison of the MIR-Estimated and Model-Calculated Fresh Water Surface Emissivities at 89, 150, and 220 GHz

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***Abstract*—The airborne millimeter-wave imaging radiometer (MIR) measurements over three lakes (surface temperature $\sim$273 K) in the Midwest region of the USA during February 1997 were used to estimate surface emissivities at 89, 150, and 220 GHz and the results were compared with those calculated from three different dielectric permittivity models for fresh water. The measurements were during clear and dry atmospheric conditions so that the column water vapor could be accurately retrieved and its effect on the MIR measurements predicted. The standard deviations of the estimated emissivities were found to be about 0.003, 0.004, and 0.008 for 89, 150, and 220 GHz, respectively. The errors of the estimation were calculated to be ± 0.005, ± 0.006, and ± 0.011 in the same order of frequency, respectively, based on the MIR measurement accuracy of ± 1 K in the brightness temperature range of 190–290 K.**

The estimated emissivities at normal incidence, under the assumption of a calm water surface, compare quite well with values generated by the model of Stogryn *et al.* [1]. These estimated values are slightly lower than those calculated from the model of Liebe *et al.* [2] at both 89 and 150 GHz. The estimated 89 GHz emissivity is higher than that calculated from the model of Ellison *et al.* [3]. Additionally, the retrievals using different models of atmospheric absorption as well as off-nadir measurements of the MIR are explored. The impact of these retrievals on the comparison of estimated and calculated emissivities is discussed.

***Index Terms*—Millimeter-wave radiometry, remote sensing, surface emissivity.**

I. INTRODUCTION

MICROWAVE remote sensing of atmospheric and oceanic parameters such as water vapor, clouds, precipitation, surface wind and temperature from aircraft and satellite platforms depends crucially on the knowledge of surface emissivity (or reflectivity) and therefore the dielectric permittivity of water. A number of models for the dielectric permittivity of water [1]–[4] have been formulated in the past decades to facilitate measurements of these parameters. At low frequencies $\leq$10 GHz, the complex dielectric permittivity, ε, of water and its temperature dependence appear to comply with Debye's model of single-frequency dielectric relaxation [3]–[5]. In the frequency range below 85 GHz covered by the special sensor microwave/imager (SSMI) or other satellite radiometers that were used to retrieve parameters like column water vapor clouds, and wind speed over ocean surface [6]–[8], the results of emissivity calculations based on the single-frequency model were not completely satisfactory [8]. Dual-frequency models based on new measurements have been formulated [1], [2], but these models lack extensive testing. More recently, the radiometric measurements at higher frequencies than 85 GHz have been used for studying and retrieving water vapor, clouds, and precipitation [9]–[11]. Thus, it is important to examine the adequacy of ε values derived from these models at frequencies $>$10 GHz for reliable retrievals of these atmospheric and oceanic parameters.

In this paper, we attempt to validate three recent models of dielectric permittivity for fresh water [1]–[3] from the 89–220 GHz radiometric measurements of the millimeter-wave imaging radiometer (MIR). MIR is a total power, cross-track scanning radiometer that measures radiation at the frequencies of 89, 150, 183.3 ± 1, 183.3 ± 3, 183.3 ± 7, and 220 GHz [12]. The measurement accuracy of the instrument is within ± 1 K in the temperature range of 190–290 K. Racette *et al.* [12] provided a more detailed description of the characteristics and operation of the instrument. For profiling of water vapor using the MIR measurements over a water surface, the surface temperature T_s and emissivity ξ calculated from a given dielectric permittivity model are the known parameters that are used as input for a retrieval algorithm [13]. However, when the atmosphere is relatively dry with total column water $W \leq 0.8$ g/cm^2, it is possible to estimate W with good precision, without a detailed knowledge of T_s and ξ, from the MIR measurements over a water, sea ice or land surface [14]–[16]. Then ξ and its frequency dependence are readily determined after W is estimated and T_s is independently measured. This procedure is explored in an effort to estimate ξ of a water surface at 89, 150, and 220 GHz. Estimation of both W and ξ from the MIR measurements depends on the selection of atmospheric absorption models; therefore, a brief discussion of the models of atmospheric absorption and water's dielectric permittivity is given in the next section. This is followed by a description of the MIR measurements and retrievals of W and ξ. Finally, a comparison between the estimated and calculated ξ values as well as the ensuing discussion and conclusion of the results are presented.

II. MODELS OF ATMOSPHERIC ABSORPTION AND DIELECTRIC PERMITTIVITY FOR WATER

A. Atmospheric Absorption

The millimeter-wave propagation model (MPM) formulated by Liebe [17] is frequently used in radiative transfer calculations, in the microwave-millimeter-wave region of the electromagnetic spectrum, in recent years [13], [18]–[20]. More recently, Rosenkranz [21] reexamined most of the available data and formulated a new model, which was used by Westwater *et al.* [20] to compute T_b values from rawinsonde data acquired at Barrow, Alaska and compared with near concurrent measurements from ground-based radiometers during March 1999. Westwater *et al.* [20] found subtle differences between the cal-

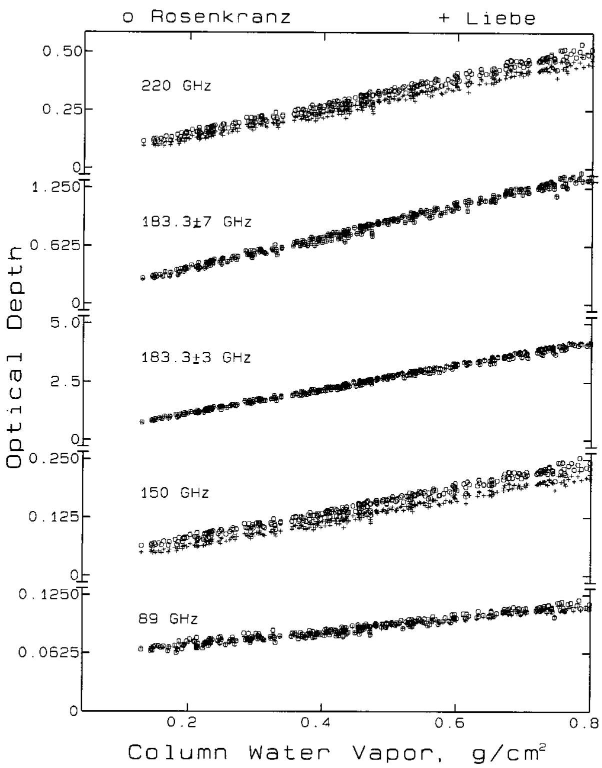

Fig. 1. Scatter plot showing the dependence of optical depth on column water vapor for several selected MIR channels. The values of optical depth are calculated based on the rawinsonde data from the Midwest USA and Alaska-Arctic regions [15].

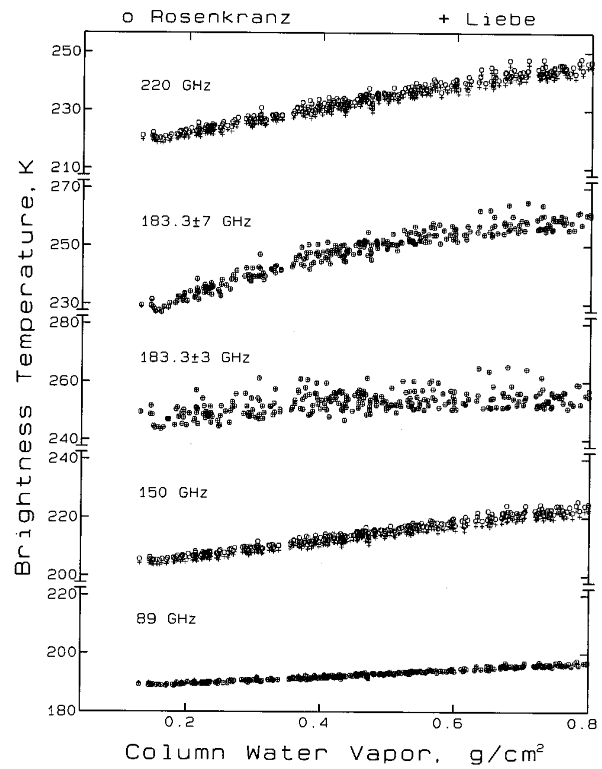

Fig. 2. Scatter plot showing the dependence of brightness temperature on column water vapor for several selected MIR channels. The calculations are based on the same rawinsonde data as in Fig. 1.

culated and measured T_b values, as well as the calculated values between the models of Liebe and Rosenkranz. To see the differences in the MIR frequency range between these two models under dry atmospheric conditions with $W \leq 0.8$ g/cm^2, we show in Figs. 1 and 2, respectively, the calculated optical depth Γ and T_b based on rawinsonde data used by Wang *et al.* [15], [16] from both WINCE and FIRE-ACE. The vertical scales from both figures are adjusted in an effort to distinctively demonstrate the variations of Γ and T_b at each frequency. In the T_b calculations, the dielectric permittivity model by Stogryn *et al.* [1] for fresh water is used to derive surface emissivity, assuming a water temperature of 274 K.

VII. Conclusion

The MIR measurements over Lake Huron, Lake Michigan, and Lake Superior under clear and dry atmospheric conditions were used to estimate surface emissivity $\xi(\nu)$ of fresh water. The estimated $\xi(\nu)$ values at $\nu = 89, 150$, and 220 GHz were compared with those calculated from three different models of dielectric permittivity [1]–[3]. Both along-track and across-track measurements were used; thus, the retrieved column water vapor W and $\xi(\nu)$ could be analyzed with respect to incidence angle (θ) up to 40°. The retrieved W values depend on θ as expected from a path length consideration. A positive gradient in W from southeast to northwest of Lake Huron during the time of the aircraft flight is revealed by the retrieval. The θ dependence of the retrieved $\xi(\nu)$ follows a pattern expected from the polarization vector of the MIR. The standard deviations of the retrieved $\xi(\nu)$ values and their frequency dependence are consistent with those estimated from statistical considerations.

The $\xi(\nu)$ values retrieved at 89, 150, and 220 GHz for fresh water are in good agreement with those calculated from the dielectric permittivity model of Stogryn *et al.* [1] in the limited temperature range near 273 K, especially if the Liebe's MPM model is used to account for the effect of atmospheric absorption [17]. When Rosenkranz's atmospheric model [21] is used the estimated $\xi(\nu)$ at 150 GHz appears low compared to all model calculations. The dielectric permittivity model of Liebe *et al.* [2] gives $\xi(\nu)$ values at both 89 and 150 GHz, which are slightly higher than the estimated values (i.e., just outside of errors based on ± 1 K measurement accuracy of the MIR). Finally, the estimated $\xi(\nu)$ values at 89 GHz are about 0.012 higher than those calculated at $T_s = 273$ K from the model of Ellison *et al.* [3] for seawater. Because the $\xi(\nu)$ values for fresh water are generally lower than those of saline water, this difference suggests a lower bound of the disagreement between estimation and calculation, unless the enhanced $\xi(89)$ can be totally accounted for by a wind-roughened surface effect. The $\xi(89)$ curve calculated from the model of Ellison *et al.* displays a milder dependence on T_s than those calculated from the other three models. It will be interesting to examine the T_s dependence of $\xi(\nu)$ and, therefore, the complex dielectric permittivity over a wider T_s range than available from the data used in this paper.